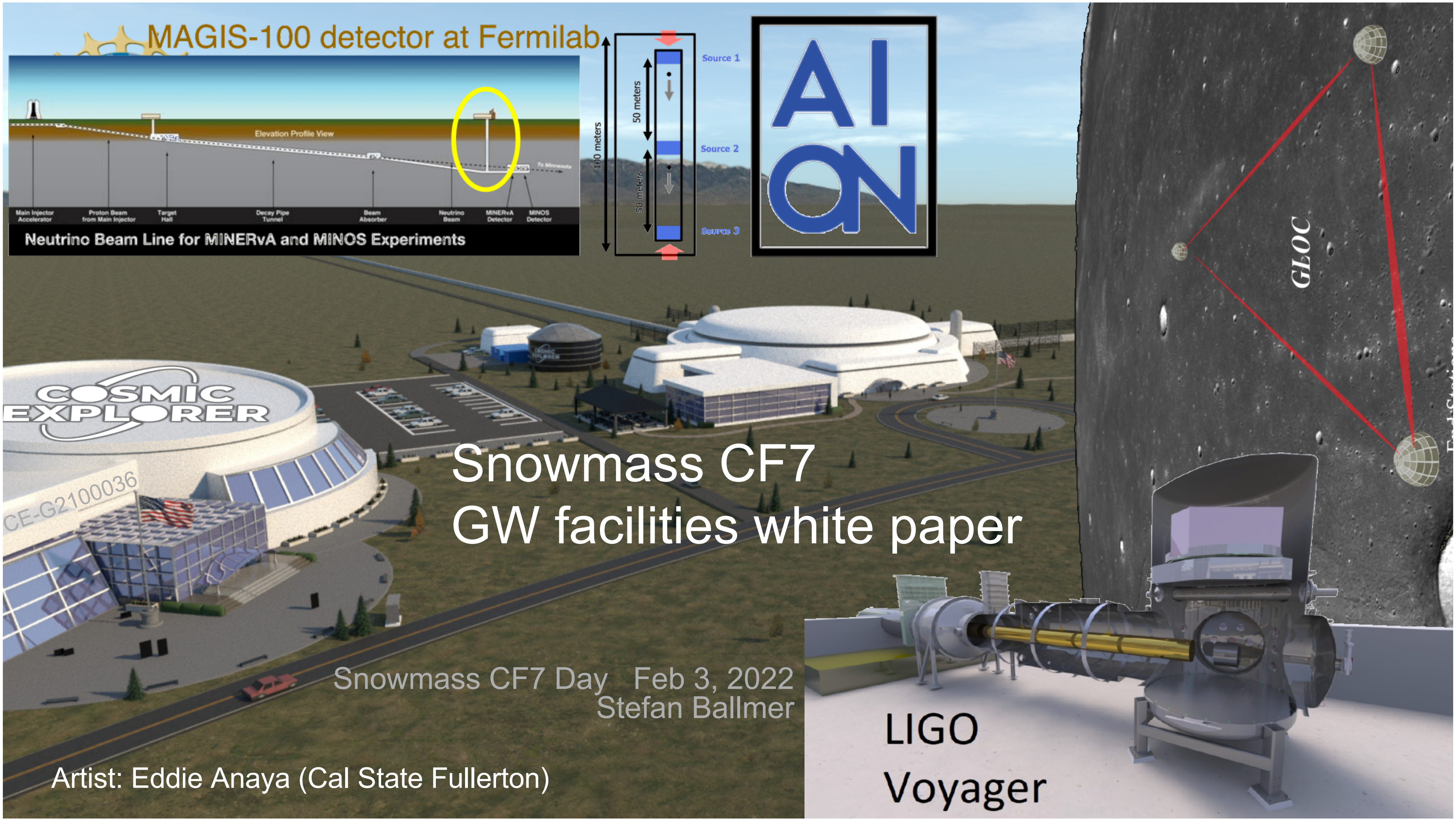
MAGIS-100 detector at Fermilab
Elevation Profile View
Main Injector Accelerator
Proton Beam from Main Injector
Target Hall
Decay Pipe Tunnel
Beam Absorber
Neutrino Beam
MINERvA Detector
MINOS Detector
To Minnesota
Neutrino Beam Line for MINERvA and MINOS Experiments
100 meters
50 meters
50 meters
Source 1
Source 2
Source 3
AION
GLOC
COSMIC EXPLORER
CE-G2100036
Snowmass CF7
GW facilities white paper
Snowmass CF7 Day Feb 3, 2022
Stefan Ballmer
Artist: Eddie Anaya (Cal State Fullerton)
LIGO
Voyager

Original LOIs to be folded into this WP:

- Cosmic Explorer: The Next-Generation U.S. Gravitational-Wave Detector (CF#010)
  (Corresponding author: Stefan Ballmer, sballmer@syr.edu)
- LIGO Voyager: A Gravitational-wave Probe of Cosmology and Dark Matter (CF#063)
  (Corresponding author: Rana Adhikari, rana@caltech.edu)
- The Atom Interferometric Observatory and Network (AION) for Dark Matter and Gravity Exploration (CF#018)
  (Corresponding author: Leonardo Badurina, leonardo.badurina@kcl.ac.uk)
- Snowmass2021 Letter of Interest: The Matter wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) Experiment (IF#136)
  (Corresponding author: Swapan Chattopadhyay, swapan@fnal.gov)
- Long-baseline Atomic Sensors for Fundamental Physics (CF#164)
  (Corresponding author: Jason Hogan, hogan@stanford.edu)
- Opportunities in gravitational physics (IF#134)
  (Corresponding author: Jason Hogan, hogan@stanford.edu)
- A deci-Hz Gravitational-Wave Lunar Observatory for Cosmology CF#239
  (Corresponding author: Jani Karan, karan.jani@vanderbilt.edu)

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- Contact me (sballmer@syr.edu) for coordination with other white papers.

Status

- Sections being written now
- Next meeting for editorial discussions:
  Wed, Feb 9 11am EDT (2022/02/9, 11am EDT)
- Minutes and planning notes:
  https://docs.google.com/document/d/1vfBAdZ0APKoADj4sVfIchhT5q14kZnIwwjFm-d2E72o/edit

Snowmass2021 - White Paper

Future Gravitational-Wave Detector Facilities

Authors: Stefan Ballmer, Rana Adhikari, Leonardo Badurina, Duncan Brown, Swapan Chattopadhyay, Peter Fritschel, Jason M. Hogan, Karan Jani, Tim Kovachy, Ariel Schwartzman, Daniel Sigg,

Abstract: Gravitational waves can provide access to a wide range of fundamental physics phenomena throughout the history of the universe. This includes access to the universe's binary black hole population throughout cosmic time, to the universe's expansion history independent of the cosmic distance ladders, to stochastic gravitational-waves from early-universe phase transitions, to warped space-time in the strong-field and high-velocity limit, and to the equation of state of nuclear matter at neutron star and post-merger densities.

This white paper discusses the gravitational-wave detector concepts than can drive the future evolution of gravitational-wave astrophysics. We summarize the most intriguing science targets for these detectors, the status of the necessary technology, and the research needed to be able to build these observatories in the 2030s. We summarize the accessible science in section 2. Section 3 discusses laser interferometer detectors: Cosmic Explorer, a ground-based third-generation gravitational-wave observatory, and Voyager, a technology upgrade proposal to existing the gravitational-wave LIGO facilities. In section 4 we look at the state of atom interferometer technology, the status of the atom interferometers facilities MAGIS and AION, as well as opportunities for potential use of this technology in gravitational-wave detectors. We highlight a number of common technologies needed for both types of detecors in section 6. Finally we place terrestrial-based gravitational-wave detectors into the future landscape of observatories that can span the whole gravitational-wave spectrum (CMB B-modes, Nanograv, LISA), and explore other future options, such as a potential lunar-based observatory.

White paper outline

- 1) Executive Summary (Stefan Ballmer,)
- 2) Top Science Goals (Duncan Brown, Jason, Karan):
    - Group by Dark Sector, Test of GR, Beyond Standard Model, Nucleosynthesis and NS physics
- * Dense matter, neutron star equation of state
- * Cosmology and Cosmic Acceleration/Dark Energy
- * Particle signatures in gravitational-wave signals
- * Dark Matter
- * Early Universe
- * Correlating gravitational wave and electro-magnetic anisotropy
- * Analytical waveform models for binary block holes
- * Testing General Relativity
- * Discovering axion/axion-like particles using gravitational-wave sources
- * New long-range forces
- * Other??

White paper outline

- 2) Top Science Goals (Duncan Brown, Jason, Karan):
    - Group by Dark Sector, Test of GR, Beyond Standard Model, Nucleosynthesis and NS physics
    - Connect narrative to other white papers

White paper outline

- 3) **Gravitational-wave new facilities and upgrades** (Stefan Ballmer, Rana Adhikari,)
    - Much of this is built on the Cosmic Explorer Horizon Study and Voyager design
- Design Choices & Technology Drivers and Choices
- Cosmic Explorer observatory
- Voyager design (Rana / Chris Wipf)
- International Partnerships, Organization and Schedule

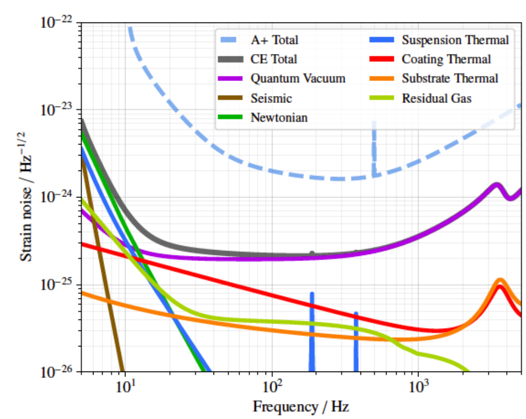


Figure 2: Estimated spectral sensitivity (solid black) of Cosmic Explorer and the known fundamental sources of noise that contribute to this total (colored curves). The design sensitivity of LIGO A+ is also shown in dashed blue. (From the Cosmic Explorer Horizon Study ?)

White paper outline

- 4) **Atom interferometers** (Jason, Tim, Ariel)
- Technology status and R&D
- MAGIS
- AION
- Future facilities?
- Tech overlap with laser interferometers?
- Possibility to share facility space with laser interferometers?

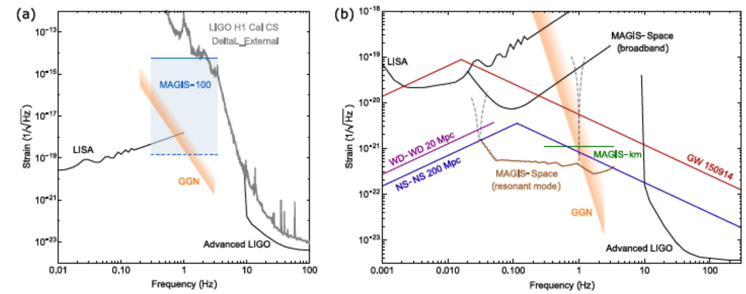


Figure 3: (a) Projected gravitational wave strain sensitivity for MAGIS-100 and follow-on detectors. The solid blue line shows initial performance using current state of the art parameters (table:futurevision, initial). The dashed line assumes parameters improved to their physical limits (table:futurevision, final). LIGO low frequency calibration data (gray) is shown as an estimate for the state-of-the-art performance in the mid-band frequency range[?]. An estimate of gravity gradient noise (GGN) at the Fermilab site is shown as an orange band. (b) Estimated sensitivity of a future km-scale terrestrial detector (MAGIS-km, green) and satellite-based detector (MAGIS-Space, brown) using detector parameters from table:futurevision. The detector can be switched between both broadband (black, solid) and narrow resonant modes (black, dashed). The resonant enhancement Q can be tuned by adjusting the pulse sequence[?]. Two example resonant responses are shown targeting 0.03 Hz ($8\hbar k$ atom optics, $Q = 9$) and 1 Hz ($1\hbar k$ atom optics, $Q = 300$). The brown curve is the envelope of the peak resonant responses, as could be reached by scanning the target frequency across the band. Sensitivity curves for LIGO[?] and LISA[?] are shown for reference. Also shown are a selection of mid-band sources including neutron star (NS) and white dwarf (WD) binaries (blue and purple) as well as a black hole binary already detected by LIGO (red). The GGN band (orange) is a rough estimate based on seismic measurements at the SURF site[?].

White paper outline

- 5) **Lunar Observatory** (Jani)
    - Section describing possible future prospect of a lunar-based detector for low frequencies

5 Lunar-based Gravitational-Wave Detectors [Karan Jani]

One of the most challenging frequency range to measure gravitational waves (GWs) is from deci-Hz to 1 Hz. This range tends to be too low for all the proposed Earth-based gravitational-wave detectors (like Einstein Telescope[?] and Cosmic Explorer[?]) and too high for the space mission LISA[?], although DECIGO[?] and other concepts[?][?] are currently being studied to detect deci-Hz GWs. The universe offers a rich set of astrophysical sources in this regime[?], whose observations will open unique tests of general relativity and physics beyond the Standard Model[?]. Here, we are proposing a lunar-based detector whose primary goal is to access this deci-Hz regime[?]. With the advent of NASA's Artemis and Commercial Crew programs, the time is ripe to consider fundamental physics experiments on the Moon.

The Moon offers a natural environment for constructing a large-scale interferometer as a detector. The atmospheric pressure on the surface of the Moon during sunrise is comparable to the currently implemented

White paper outline

- **6) Common technologies and research opportunities (Ariel, Daniel Sigg, ..)**
- DOE national labs role in the field
- Emphasize specific tech examples and DOE labs related capabilities
    - Examples: vacuum, Newtonian noise cancellation, etc.
- Touch on land use issues for ground-based detectors

White paper outline

- 7) **Outlook section** **(Stefan, Jason, Karan,TBD)**.
- Lunar observatory
- Broad observation band
- Observation capability in all bands, with localization
- Larger landscape:
    - LISA
    - NanoGrav
    - CMB S4

- 8) **Related White Papers**

- 9) **Summary**

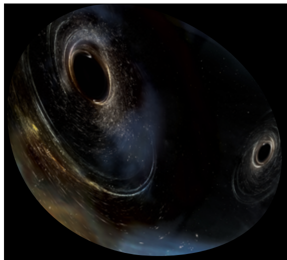
Next Steps & Summary

- In the process of writing subsection, next editorial meeting:

  Wed, Feb 9 11am EDT (2022/02/9, 11am EDT)

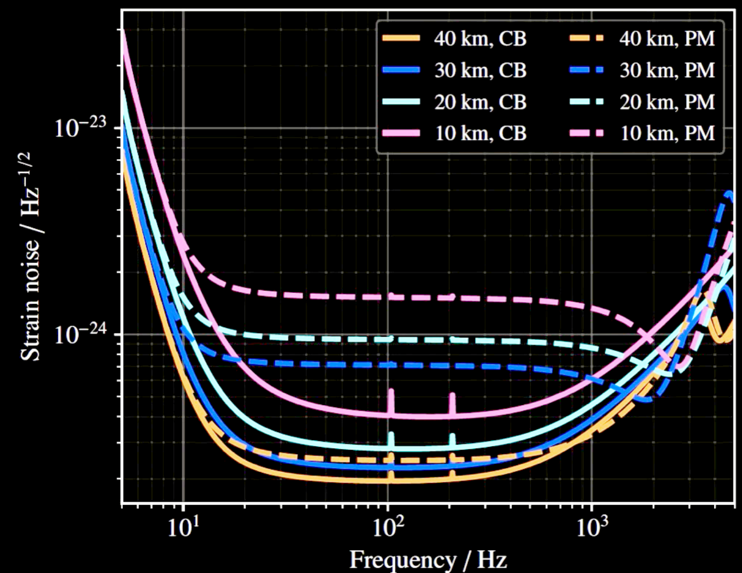
- Targeting first close-complete draft by end of Feb
- Final version Mid-March?
- Minutes and planning notes:
  https://docs.google.com/document/d/1vfBAdZ0APKoADj4sVfIchhT5q14kZnIwwjFm-d2E72o/edit
  https://syracuseuniversity.zoom.us/j/93534112167?pwd=L1U0S3lxUGFTUmpMaUpBVGI0MlICZz09

End



Cosmic Explorer

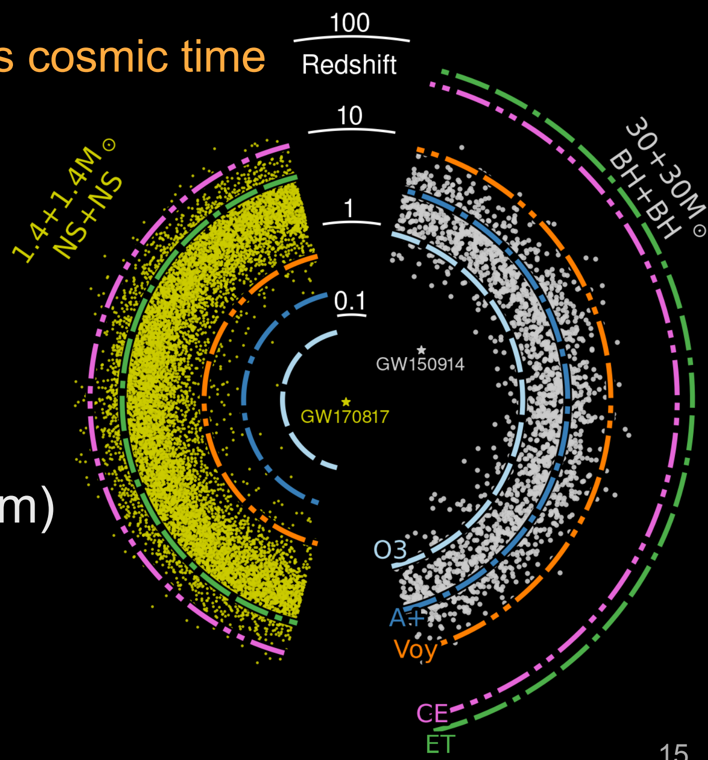
- Cosmic Explorer Reference concept
  - Includes a 40km and 20km interferometer
  - Provides the cosmological reach for binaries
  - Relies extensively on proven technology
  - Can incorporate new technologies



Why terrestrial interferometry?

- Science goals:
  - Observe stellar to intermediate mass mergers across cosmic time
  - Josh's talk will go deeper on the science goals
- Detector requirements:
  - Highest frequency of interest: approx. 5kHz
  - Strain sensitivity to have cosmological reach.

➔ Requires high-power Fabry-Perot cavities of O(40km) not practical in space (radiation pressure)



Reference Design

- Guiding principles:
    - "Build on what works"
      Basic configuration, silica technology, 1um laser
    - "With improvements where knowledge has advanced"
      Match antenna to known sources, wave front control, squeezing, etc.
    - "But keep it flexible" to take advantage of technology development
      Possible upgrade path to cryogenic, 2um, or Crystalline Coatings

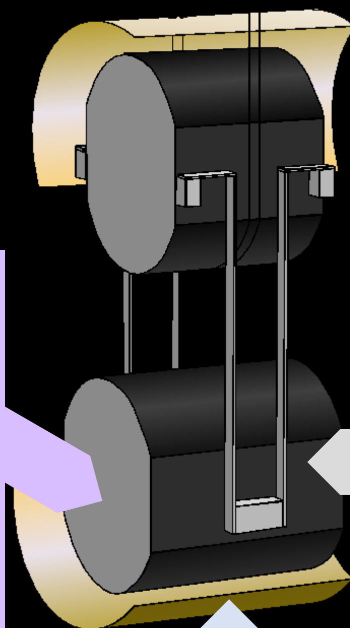
- Layout and changes compared to Advanced LIGO…

Configuration changes compared to Advanced LIGO

- Longer arm cavities (4km→40km)
- Larger test masses (m=40kg, ø=34cm →m=320kg, ø=70cm)
  - Minimal possible spot size for 40km (@ 1um) is 12cm, double of Advanced LIGO (Phys. Rev. D 103, 122004 (2001))
  - Reduction in radiation pressure noise
- 2nd input mode cleaner for frequency stabilization (arXiv:2107.14349)
- Beam reduction telescopes on arm-side of beam splitter
- Lower-loss signal recycling cavity (e.g. BS orientation)
- Scaled filter cavity (compared to A+)
- Homodyne readout (same as A+)
- Larger vacuum system (cost-critical)

Cryogenic interferometry at 2um

CORE IDEAS (Voyager concept)



① Amorphous silicon coating

- Reduces thermal noise.
  Prospect of a **4-7x** reduction from aLIGO level
- Favors **2 μm** wavelength

② Crystalline silicon substrate

- Improves quantum noise.
  200 kg mass, **3 MW** power
- High thermal conductivity, ultra-low expansion at **123 K**

③ Radiative cooling

- Still efficient at **123 K**
- Suspension design not constrained by cryogenics

Adhikari et al. CQG 37 165003 (2020)